Regulatory Review Discussion
Navy's Proposed LNAPL Transport Model for the Navy Red Hill Facility

Presented to:
Red Hill AOC 6/7 Parties

July 11, 2019

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&
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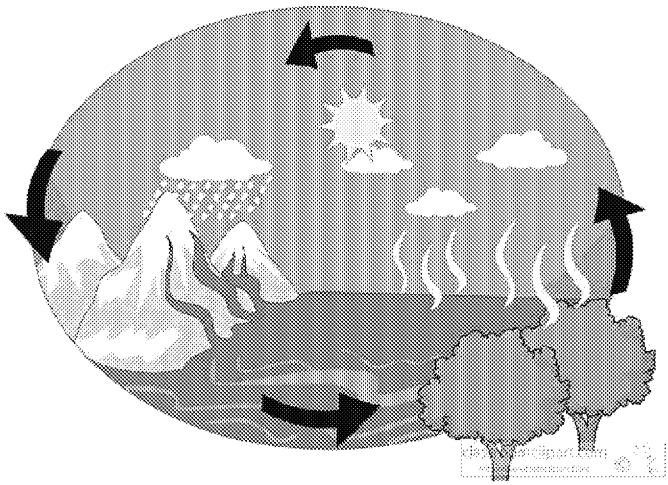
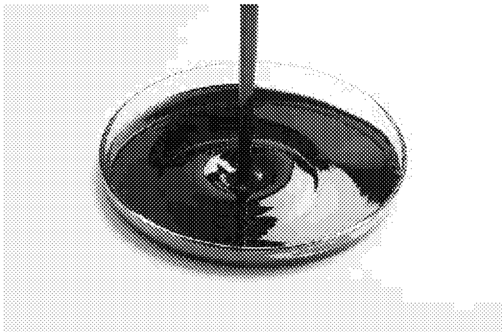
Thank You Navy Team



- The proposed model is a step forward
  - Will handle dynamic questions
- It reduces computational intensity
  - As compared to fully 3-phase codes
- LNAPL transport questions are critical
  - How far?
  - How fast?
  - In what directions?
  - Can it be captured by RH Shaft?

The Global Question: How to Define the LNAPL Source Term(s)?

Topics



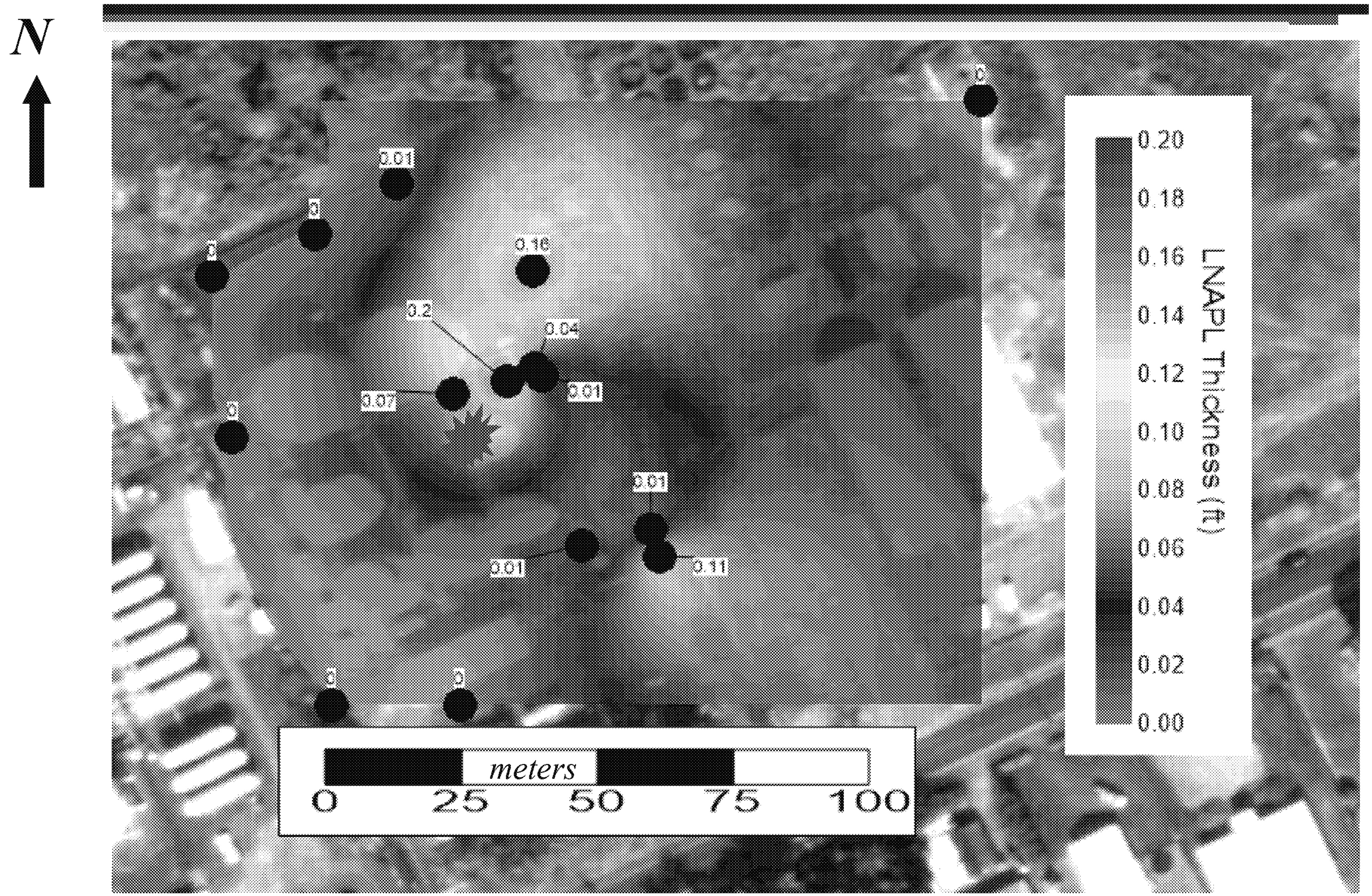
- Discussion of related Navy request items:
  - Aloha Petroleum Release, Hilo
  - 2-D LNAPL model example
- Discussion of the proposed LNAPL model
  - Regulatory summary position
  - EPM assumption
  - Lumped homogeneity
  - Parameter determinations
  - Existing conditions
  - Consistency criteria
- ***No model or modeling is perfect***
  - ***But we can evaluate important aspects***
  - ***Conservatively infer ranges***

Aloha Petroleum Release Summary

- 14,700 gallons released on Nov 1, 2011
  - Diesel tank overfill
  - Measured by meter & timing
- LNAPL identified at distal wells after release
  - MW-1 ~140-ft away
  - Travel could be double that (radial flow)
  - ~ 280-ft distance in less than 4 days
    - Perhaps further (undelineated)
  - 400-ft plume after new delineation (~ 3 mo)
- LNAPL spreading appeared rapid
  - Never observed greater than 0.25-ft (P4)
    - Except for day of max ~ 10-inches
  - Did not follow g.w. gradient
  - Did not appear strongly affected by dip
  - Dissipated to < 0.1-ft in one well by 2014
  - No dissolved-phase detected 2011 or after
    - But dissolved-oxygen depletion evident

Observed LNAPL*: January 2012

(* partial data augmented)

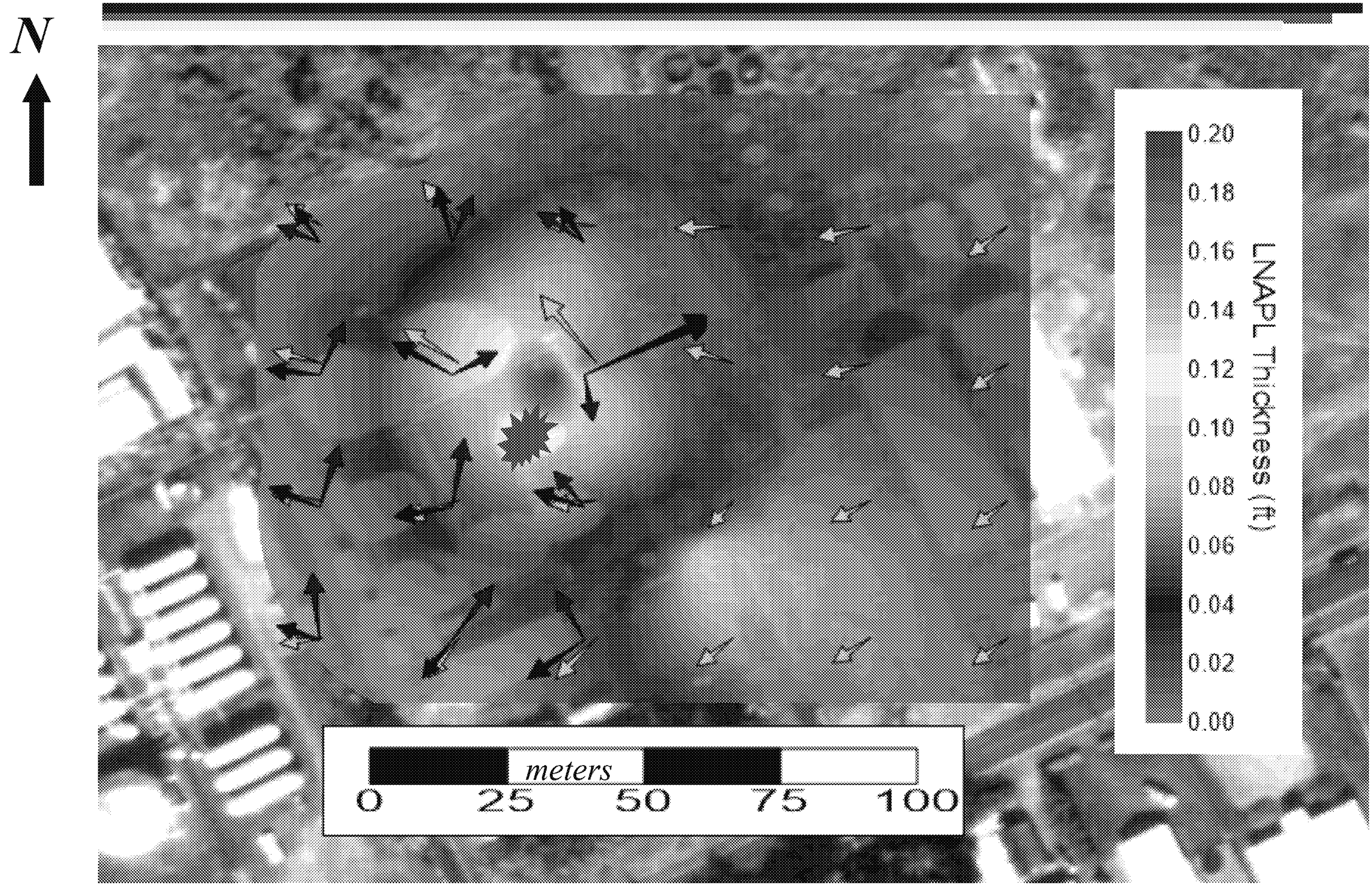


Observed LNAPL: March 2014

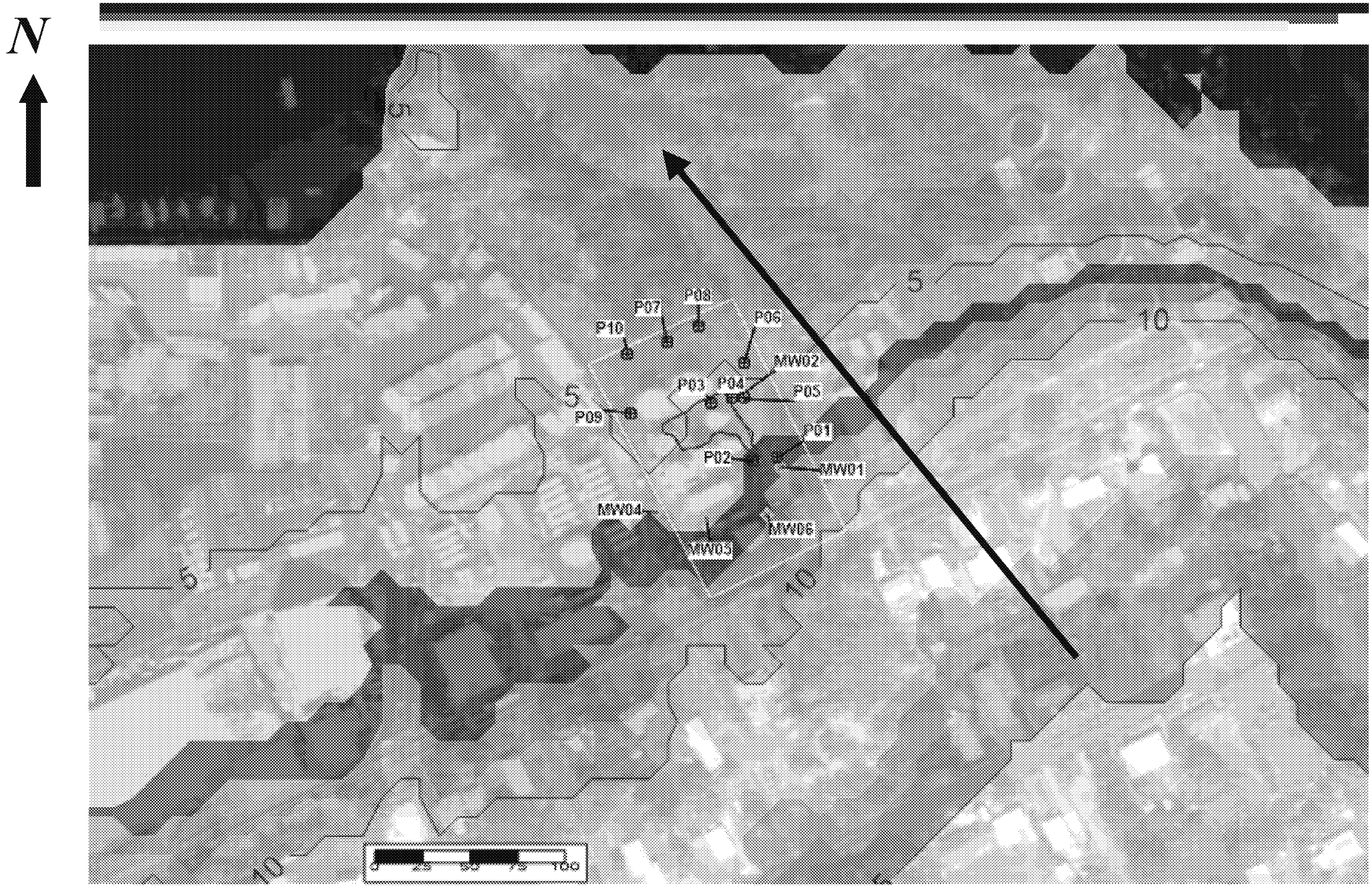
(a 98% relative reduction since early 2012)

LNAPL Distribution & Gradient Vectors

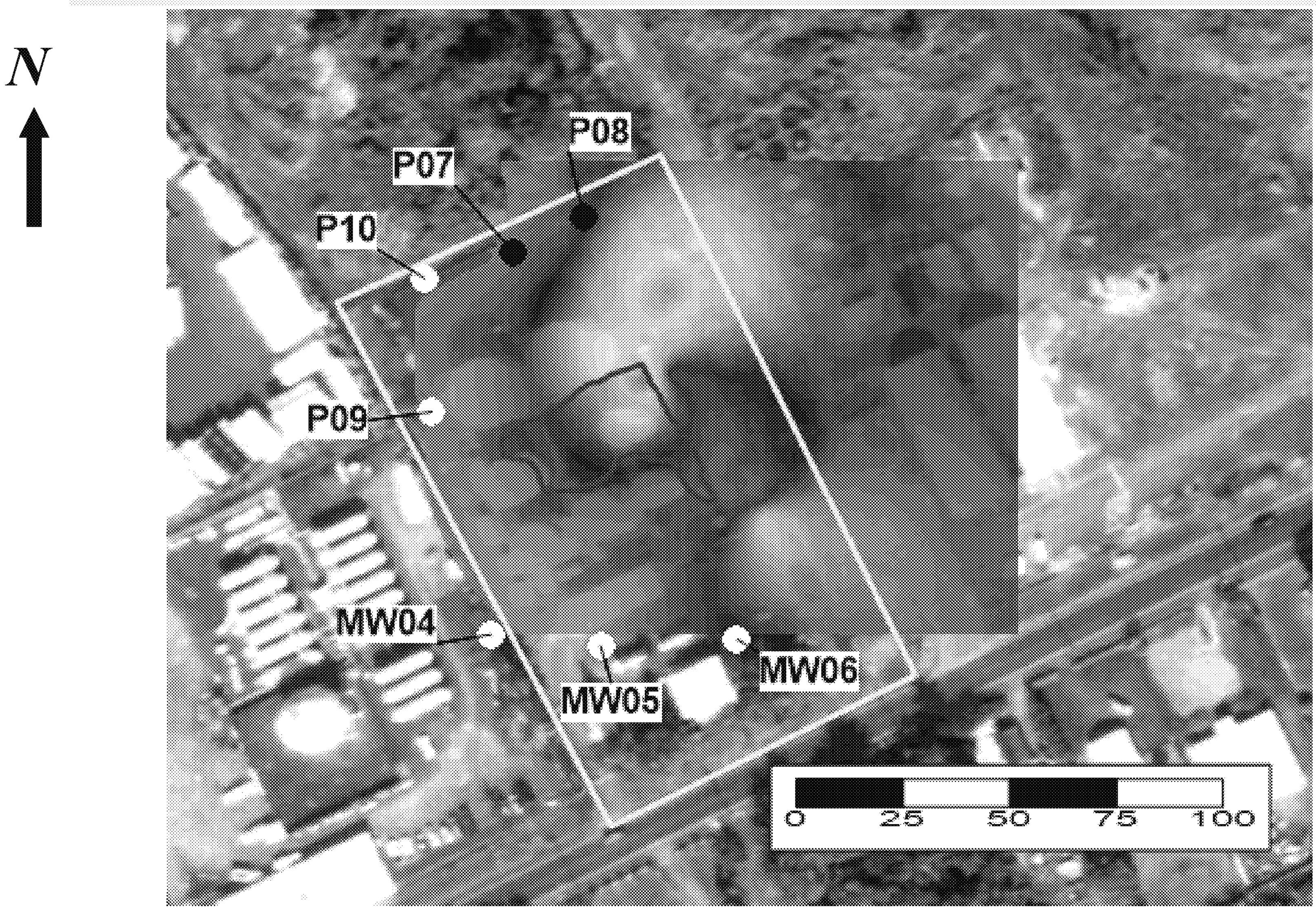
(February 2012; 99 days after the release)



Local Area Topography

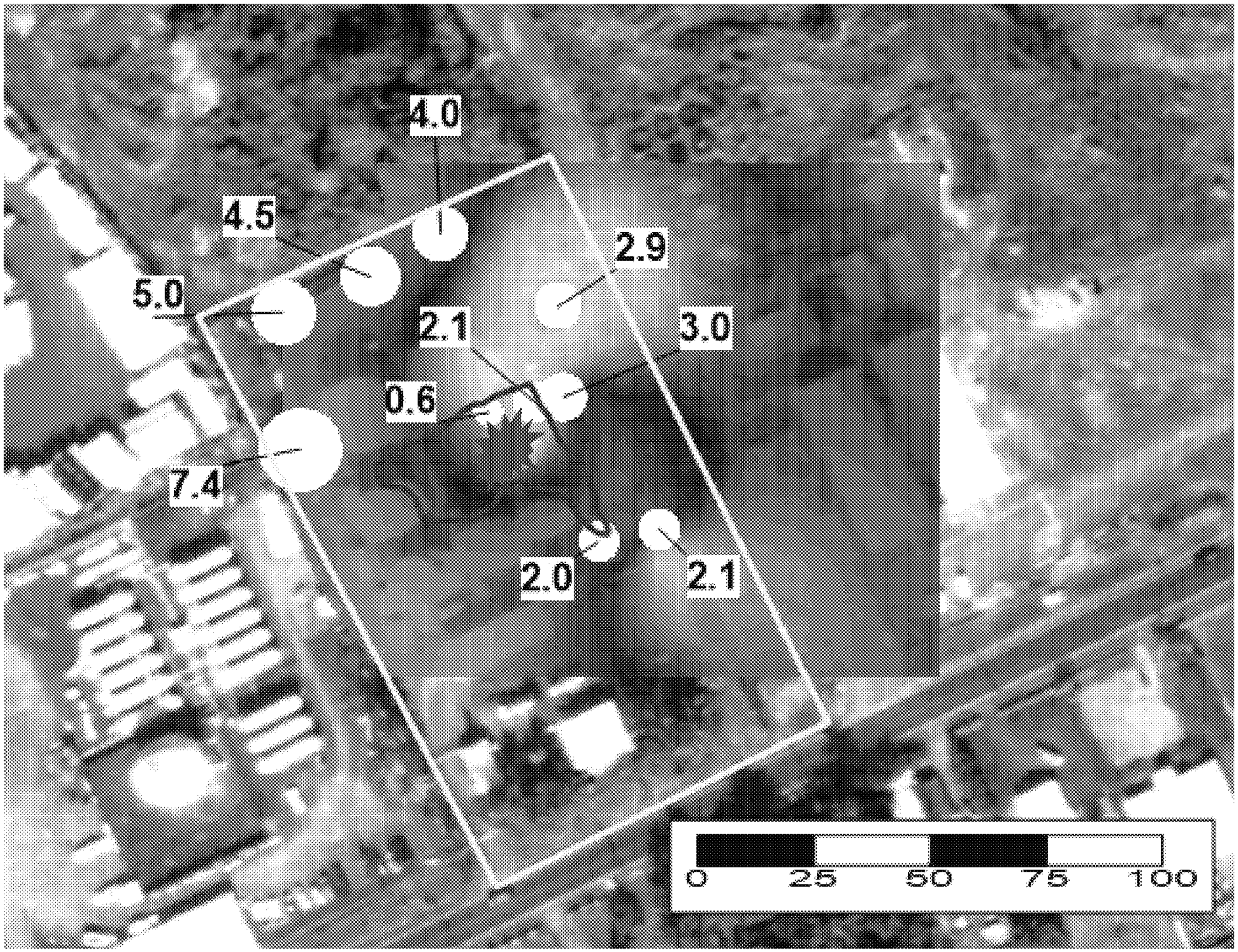


January 2012 LNAPL Plume with ND GW

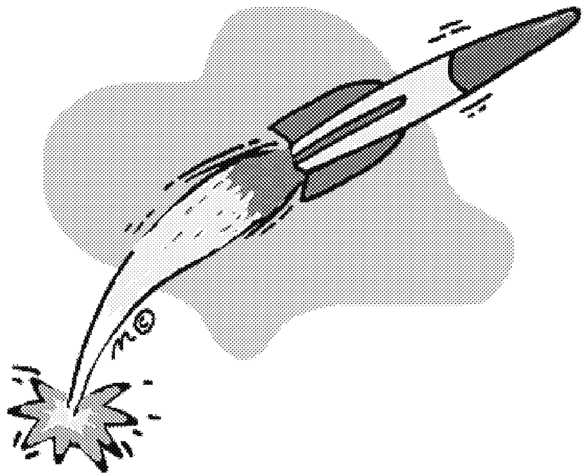


Dissolved-Oxygen (~9.3 mg/l pristine)

N



The Example 2-D MAGNAS3 LNAPL Model



- Simply an example of possible approaches
  - Done to note that it can be done
- Site geology from 3-D model
- Parameters – hypothetical
  - Based on collective experience
- It is a numerical conceptual framing
  - It was for discussion purposes only

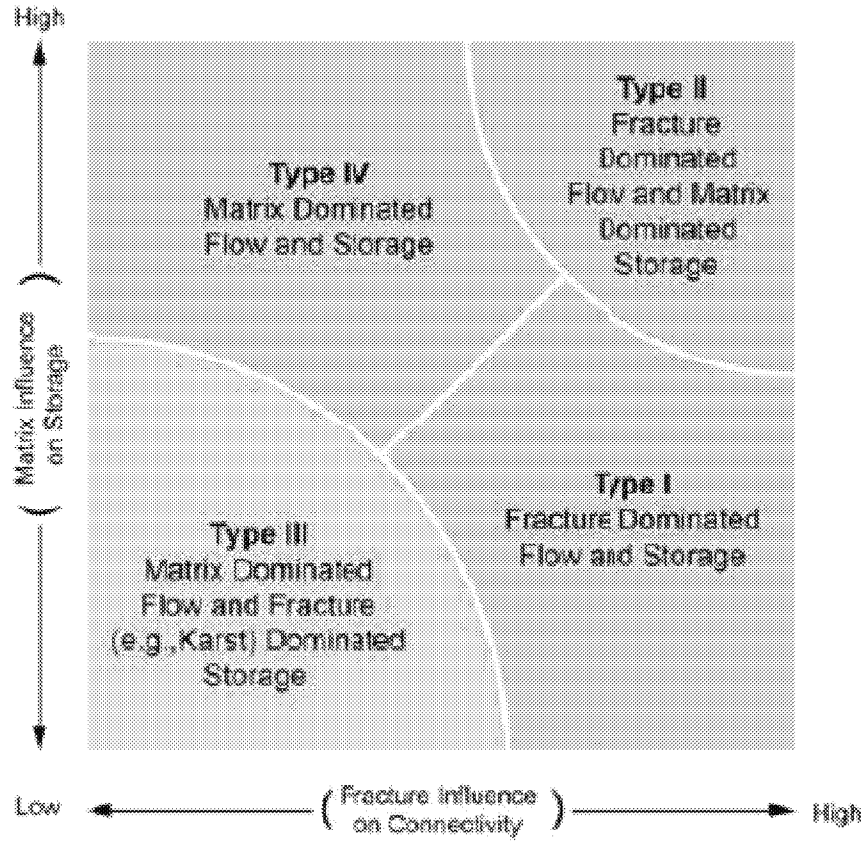
The Equivalent Porous Media Assumption

Typically applicable in well-behaved systems.

Typically has scale dependencies.

What about this particular system?

Types of Fracture/Void Regimes



"Single porosity EPM-type models are only applicable for fractured rock systems when the consequences of severe simplification of the system have been addressed."

Source: Characterization, Modeling, Monitoring, and Remediation of Fractured Rock, 2015

What Scale Applies for an EPM?

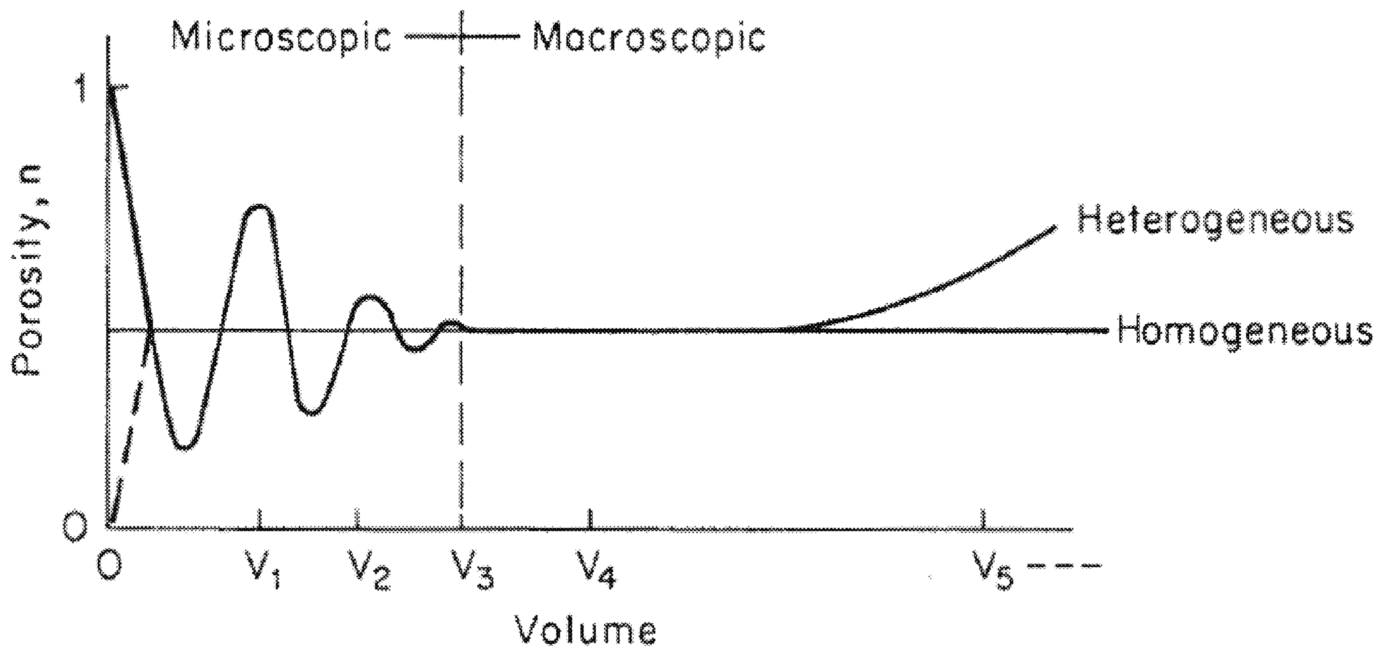
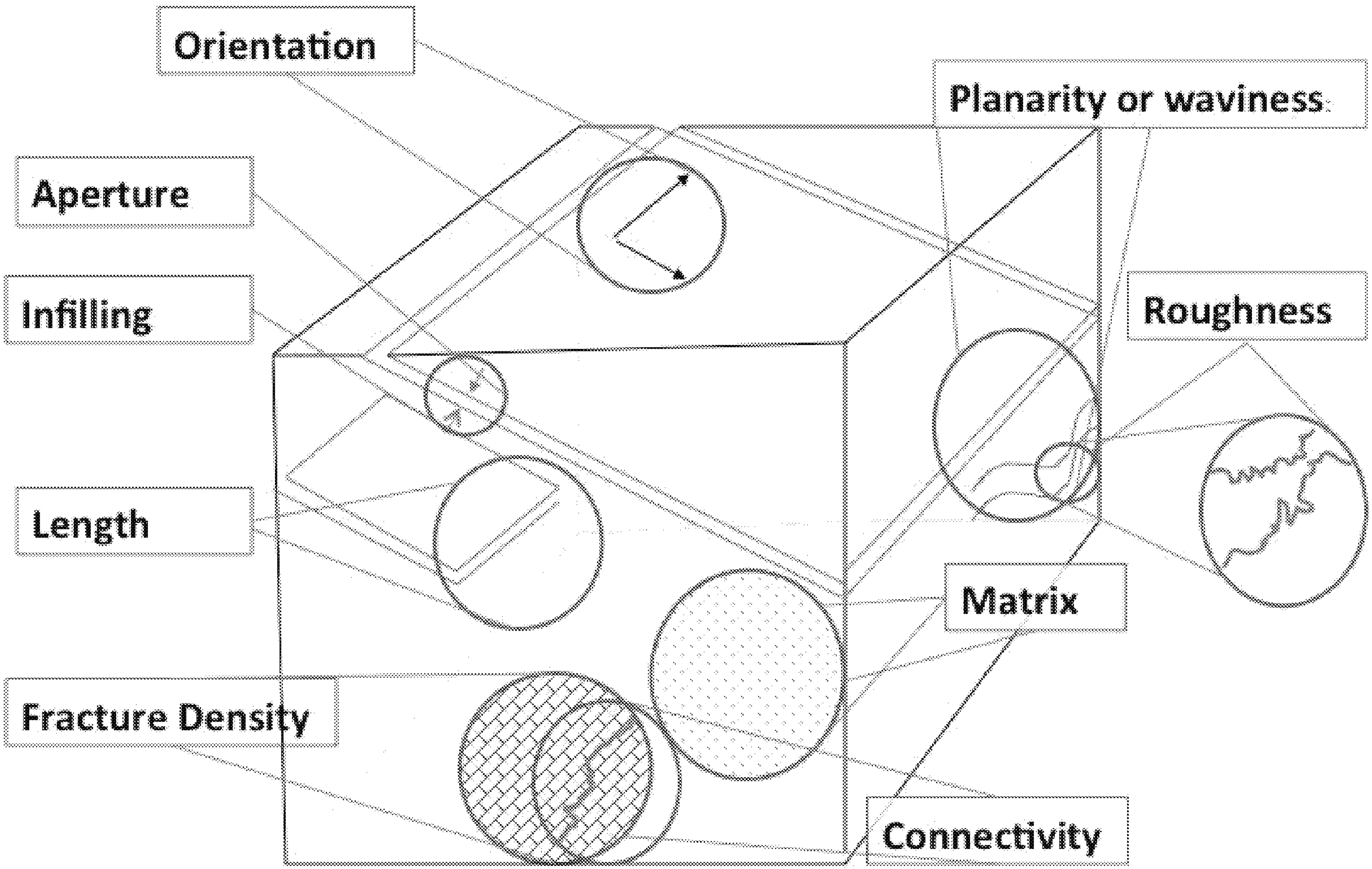


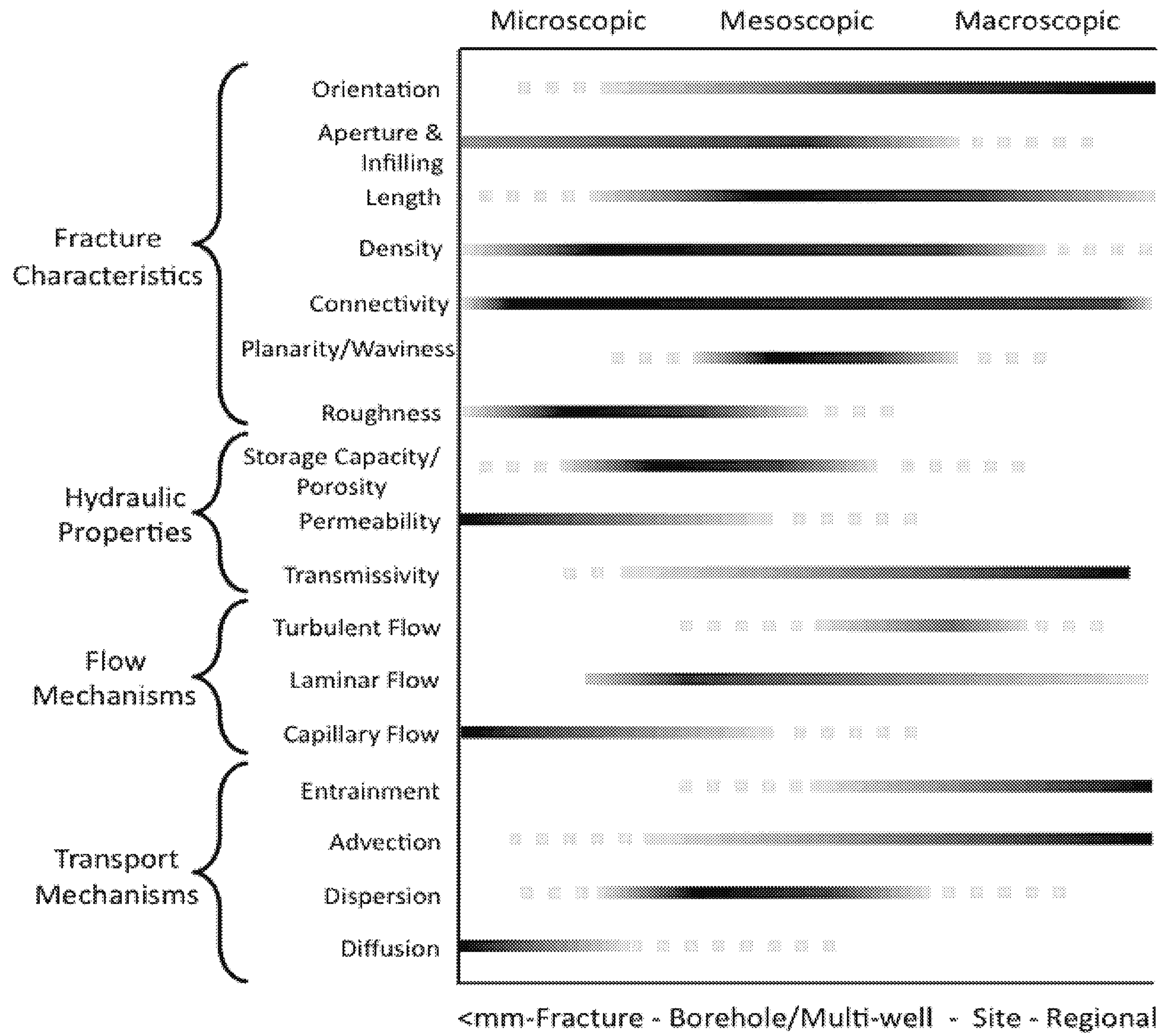
Figure 2.26 Microscopic and macroscopic domains and the representative elementary volume V_3 (after Hubbert, 1956; Bear, 1972).

Freeze & Cherry, 1979

ITRC Fractured Rock CSM - Architecture

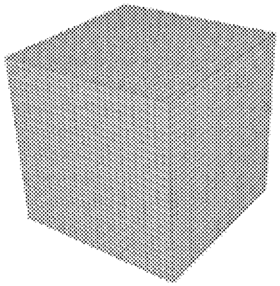


Relative Scale of Factors

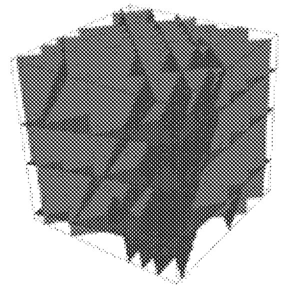


mm - millimeter

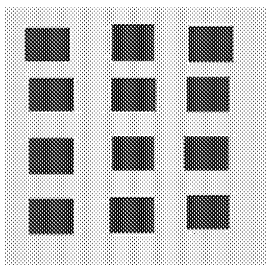
Ways to Model Geologic Architectures



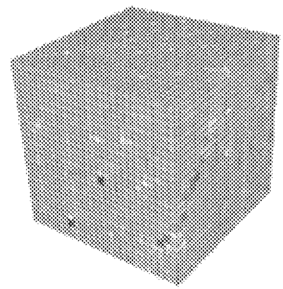
Homogeneous
Continuum



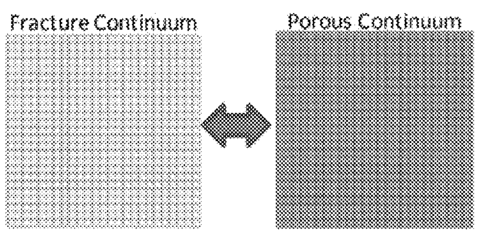
Discrete Fracture
Network Model



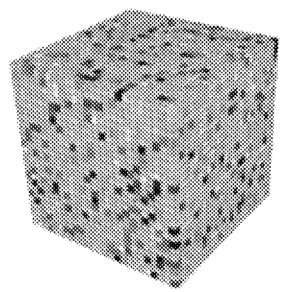
Dual Porosity – continuum with fracture network properties embedded with storative "lumps"



Continuum
Conditioned to DFN,
Background EPM



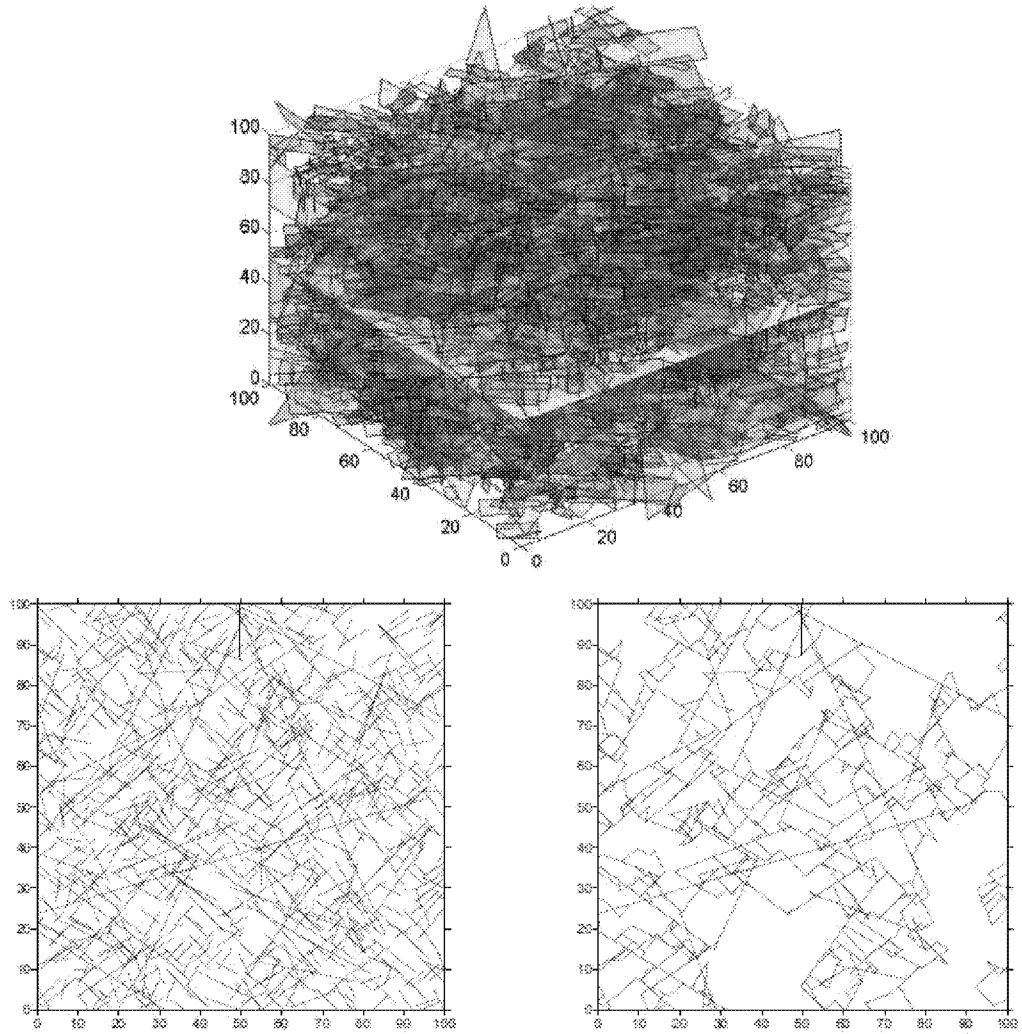
Dual Permeability – Coupled continuum simulations: one for fractures and one for matrix



Random Stochastic
Continuum

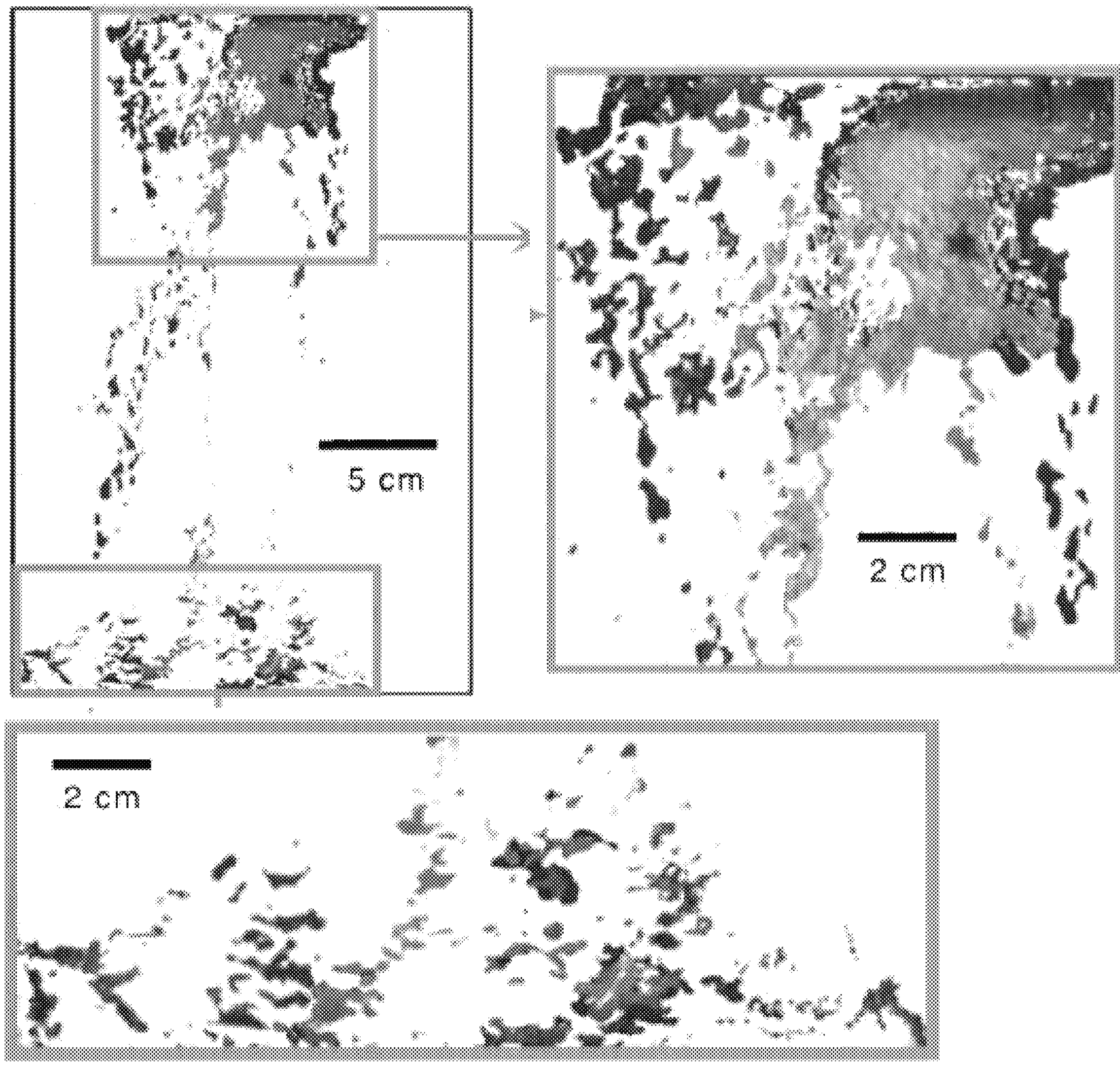
Fractured Bedrock Field Methods and Analytical Tools, 2010

Architecture Rendering of a Specific System



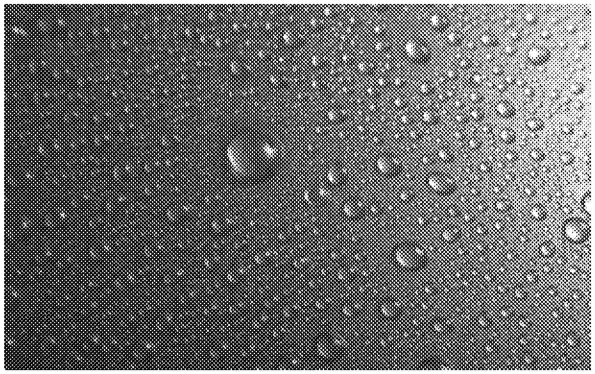
Donald M. Reeves, Rishi Parashar and Yong Zhang; Desert Research Institute

Example NAPL Distribution in a Fracture



Geller et al., 2000

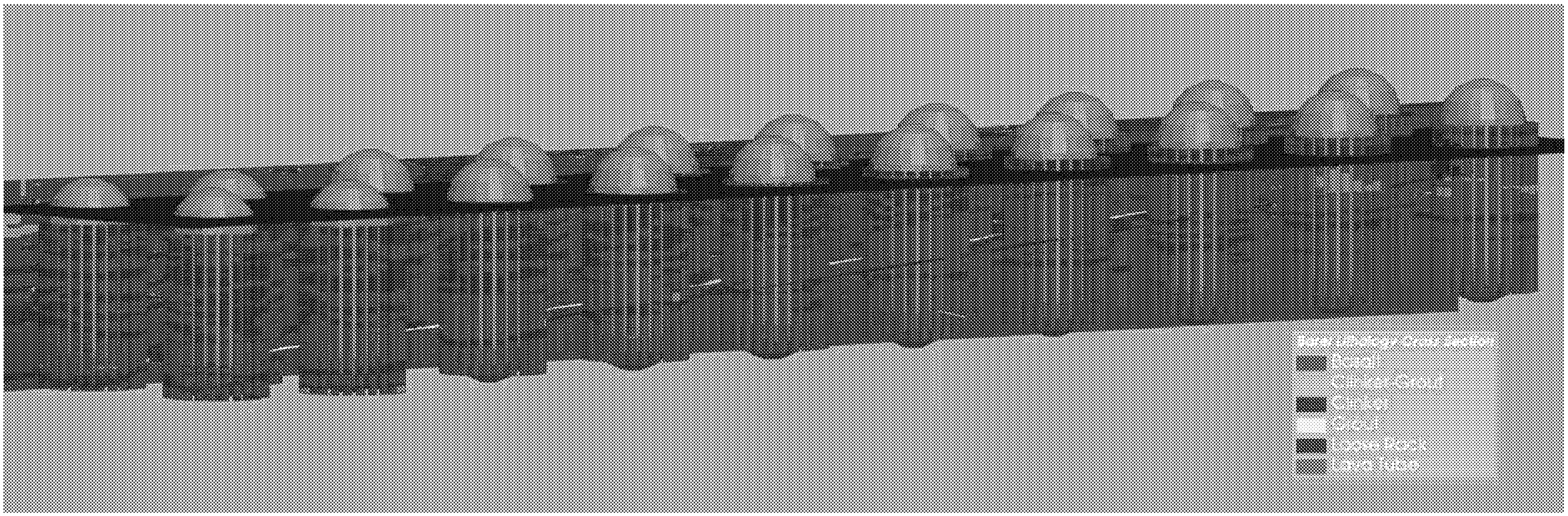
EPM Summary



- Need to define scale of applicability
  - Based on field mapping & bore data
- How is the void system interconnected?
  - At what scale?
  - Contrasts between lateral & vertical
- How are NAPL complications addressed?
  - Fingering
  - Bridging
  - Interference
  - Film transport

Lumped Homogeneity

The Geologic Distributions Are Complex



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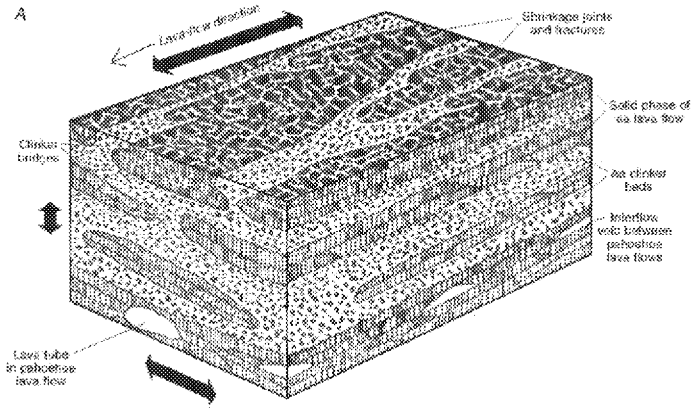
The Vadose Zone is Densely Logged



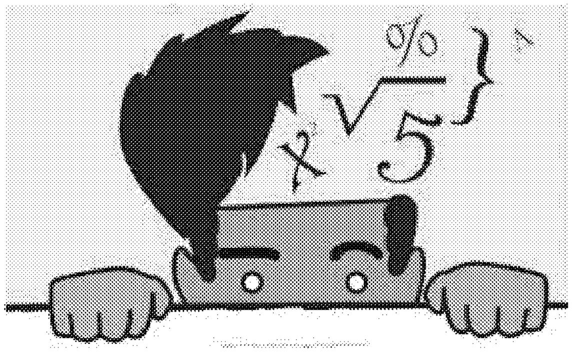
- NAPL migration is at least as complex as g.w. flow
- We already have 3-D geologic models
- Lumped modeling is limited
  - Side-stepping flow
  - Cascade flow
  - Pooling flow
  - All are functions of geology
- Key questions would remain
- Potentially non-conservative

Parameters/Inputs

Parameter Inputs

- Fluid & IFT properties
  - Likely suitable as provided
- Hydraulic K – Each HSU
  - Ranges suitable
  - HSU-dependent
- Porosity – Each HSU
  - Field ranges suitable
  - Lab ranges not likely applicable
- Capillary values – Each HSU
  - If applicable
  - Void/fracture analysis
- Residual saturation – Each HSU
  - Lab values not reliable
  - Analytic TPH ranges potential

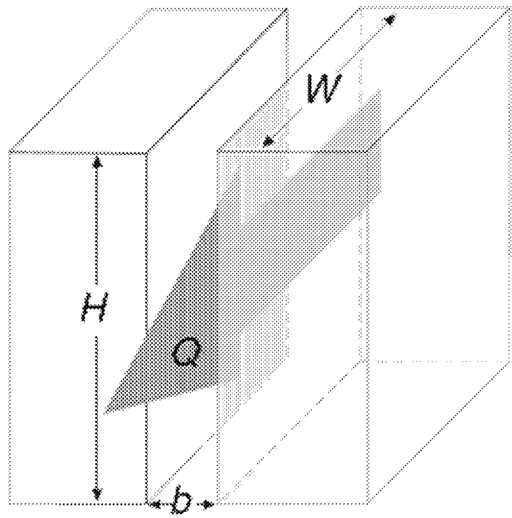
Flow in Fractures/Voids



$$Q = -\frac{\rho g}{12\mu} b^3 \partial h$$

$$K = \frac{2b^2 \rho g}{12\mu}$$

For "simple" fractures



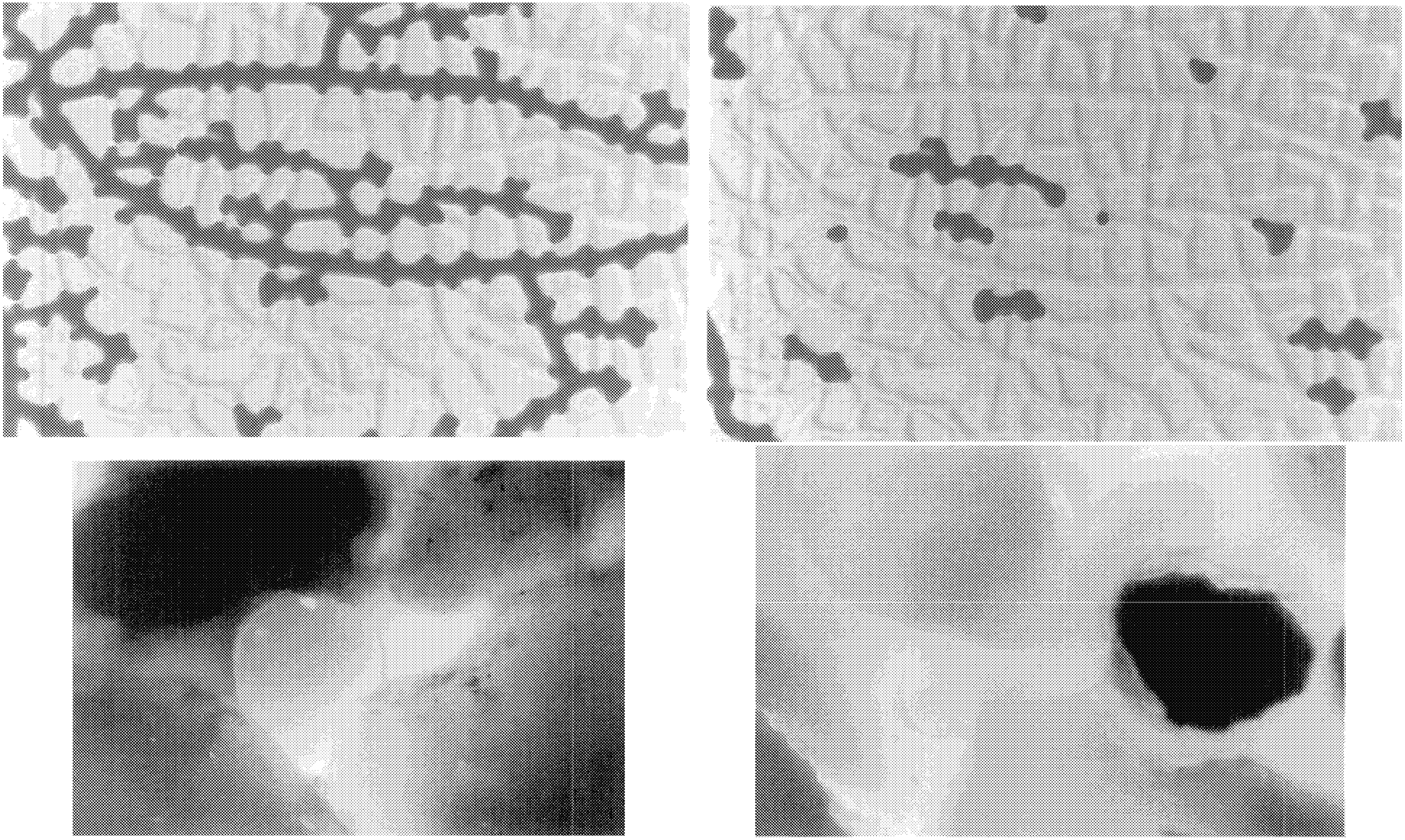
Holy exponential cow!

Suggested for "real" fractures with aperture/length correlations

$$Q = -\frac{4\rho g}{3\mu(\pi\alpha)^2} b^5 \partial h$$

after Climczak et al., 2009

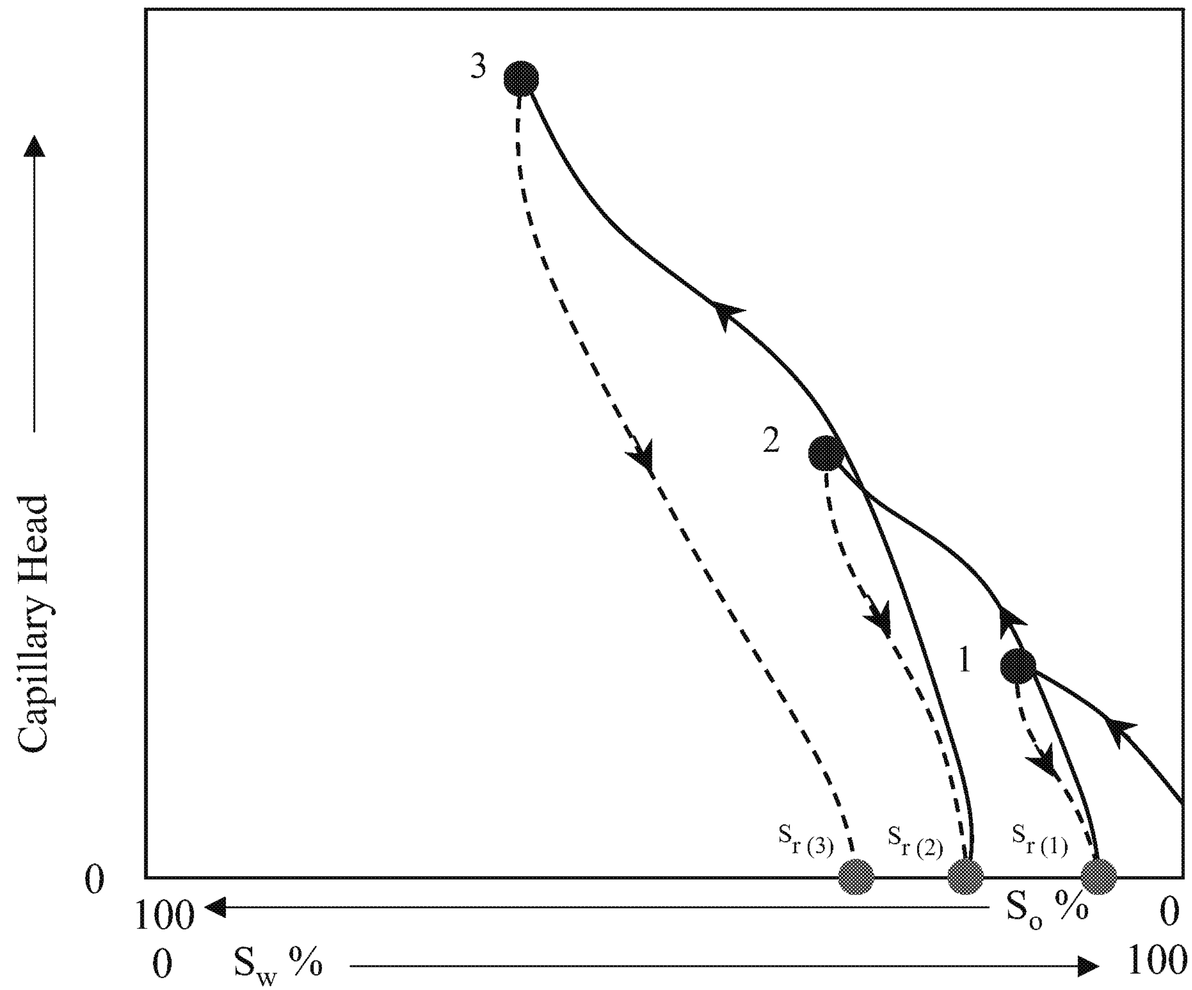
Oil Displacing Water & Residual Oil



(Source: Wilson et al., 1990; EPA 600/6-90/004)

Residual is Not a Constant

(rather, it varies with saturation history)



(After Pickell et al. 1966; modified by Adamski,2005)

Initial vs. Residual Saturation Relationship
(for these specific study soils & oils)

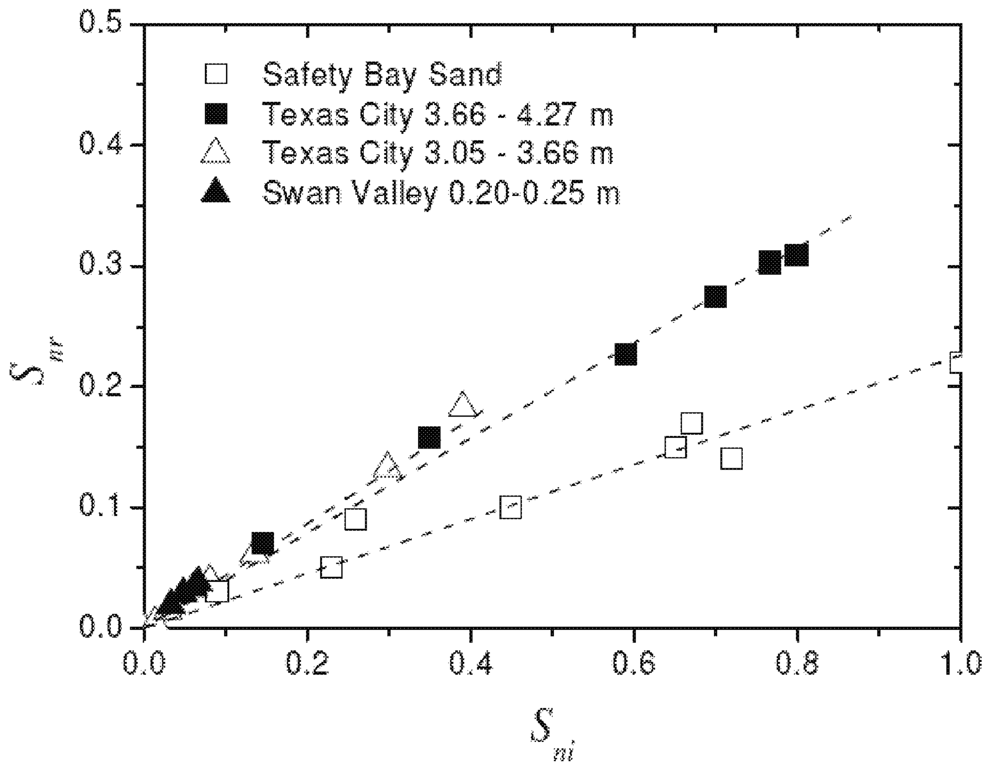
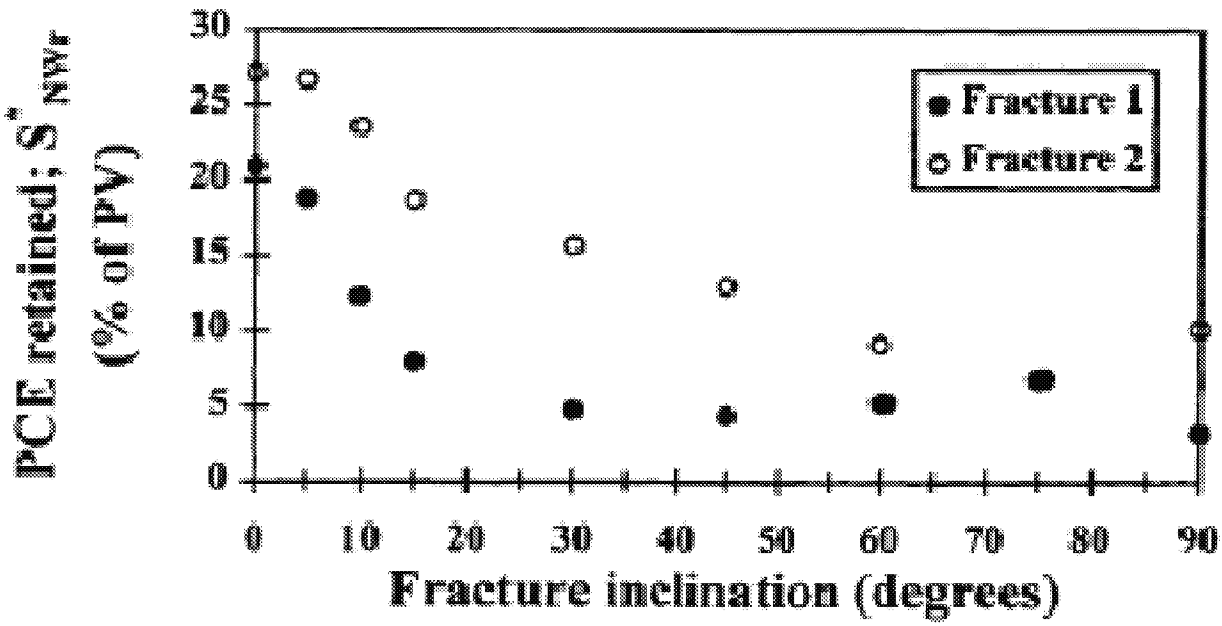


Fig. 4. Residual NAPL saturation, S_{nr}, as a function of initial NAPL saturation, S_{ni}, for the samples of the present study and for the Safety Bay Sand of Steffy *et al.* 1997. Symbols show measured values and lines show the fitted linear regression $S_{nr} = bS_{ni}$.

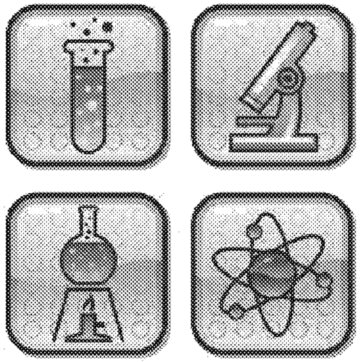
(From Johnston, C., & Adamski, M., 2005)

Residual Varies with Dip of Void Feature



(Source: Longino, 1998)

Distant Example – Approach
Snake River Infiltration Tests



- Infiltration tests used to calibrate model
  - Dual-perm model (TOUGH2)
  - Calibrate to infiltration fronts
- Interfacial fracture scale vastly reduced
  - By 0.01 – 0.10
  - To handle differential flow
- Fracture porosity was highly sensitive
  - And required significant calibration
  - Larger than packer testing suggested
  - Consistent with large-scale pump tests
- In brief, designed field data led to calibration
  - But for variably saturated water flow
  - NAPL is much more complex

Example – Geologic Framework

Zone	D_H (m)	D_V (m)
0.0 – 0.2	1.0	1.0
0.2 – 0.4	2.0	1.0
0.4 – 0.6	3.0	1.0
0.6 – 0.8	4.0	1.0
0.8 – 1.0	2.0	1.0
Rubble zone	0.1	0.1
Lower basalt	2.0	1.0

Table 1: Zonal fracture spacing.

Zone	Number of Samples	Fracture Permeability (m^2)	Fracture Aperture (m)	Fracture Porosity (–)
0.0 – 0.2	2	1.0×10^{-13}	8.5×10^{-5}	2.6×10^{-4}
0.2 – 0.4	6	4.1×10^{-13}	1.5×10^{-4}	3.0×10^{-4}
0.4 – 0.6	12	4.0×10^{-13}	1.6×10^{-4}	2.7×10^{-4}
0.6 – 0.8	14	1.9×10^{-13}	1.2×10^{-4}	1.8×10^{-4}
0.8 – 1.0	9	1.1×10^{-12}	2.1×10^{-4}	4.2×10^{-4}
rubble zone	1	1.1×10^{-9}	8.6×10^{-4}	2.6×10^{-4}
lower basalt	7	3.5×10^{-10}	1.3×10^{-3}	2.6×10^{-2}

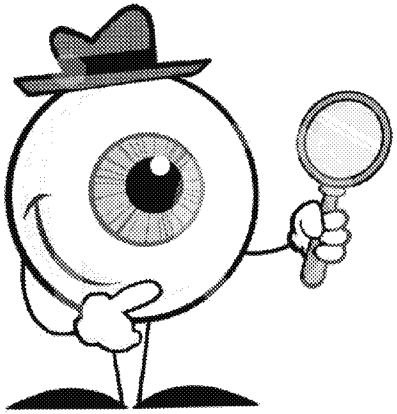
Zone	Fracture Properties						Matrix Properties			
	Porosity scaling factor	porosity (–)	van Genuchten			Corey	permeability (m^2)	porosity	van Genuchten	
			α (Pa^{-1})	m (–)	A_{fm} (–)	A_{fm} (–)			α (Pa^{-1})	m (–)
0.0 – 0.2	50	0.013	5×10^{-4}	0.5	0.01	0.1	1.0×10^{-14}	0.2	5×10^{-5}	0.25
0.2 – 0.4	50	0.015	5×10^{-4}	0.5	0.01	0.1	1.0×10^{-14}	0.2	5×10^{-5}	0.25
0.4 – 0.6	50	0.014	5×10^{-4}	0.5	0.01	0.1	1.0×10^{-14}	0.2	5×10^{-5}	0.25
0.6 – 0.8	50	0.009	5×10^{-4}	0.5	0.01	0.1	1.0×10^{-14}	0.2	5×10^{-5}	0.25
0.8 – 1.0	50	0.021	5×10^{-4}	0.5	0.01	0.1	1.0×10^{-14}	0.2	5×10^{-5}	0.25
Rubble zone	5	0.129	5×10^{-4}	0.5	0.01	0.1	1.0×10^{-14}	0.2	5×10^{-5}	0.25
Lower basalt	5	0.013	5×10^{-4}	0.5	0.01	0.1	1.0×10^{-14}	0.2	5×10^{-5}	0.25

Source: Unger et al, 2004

Consistency Criteria

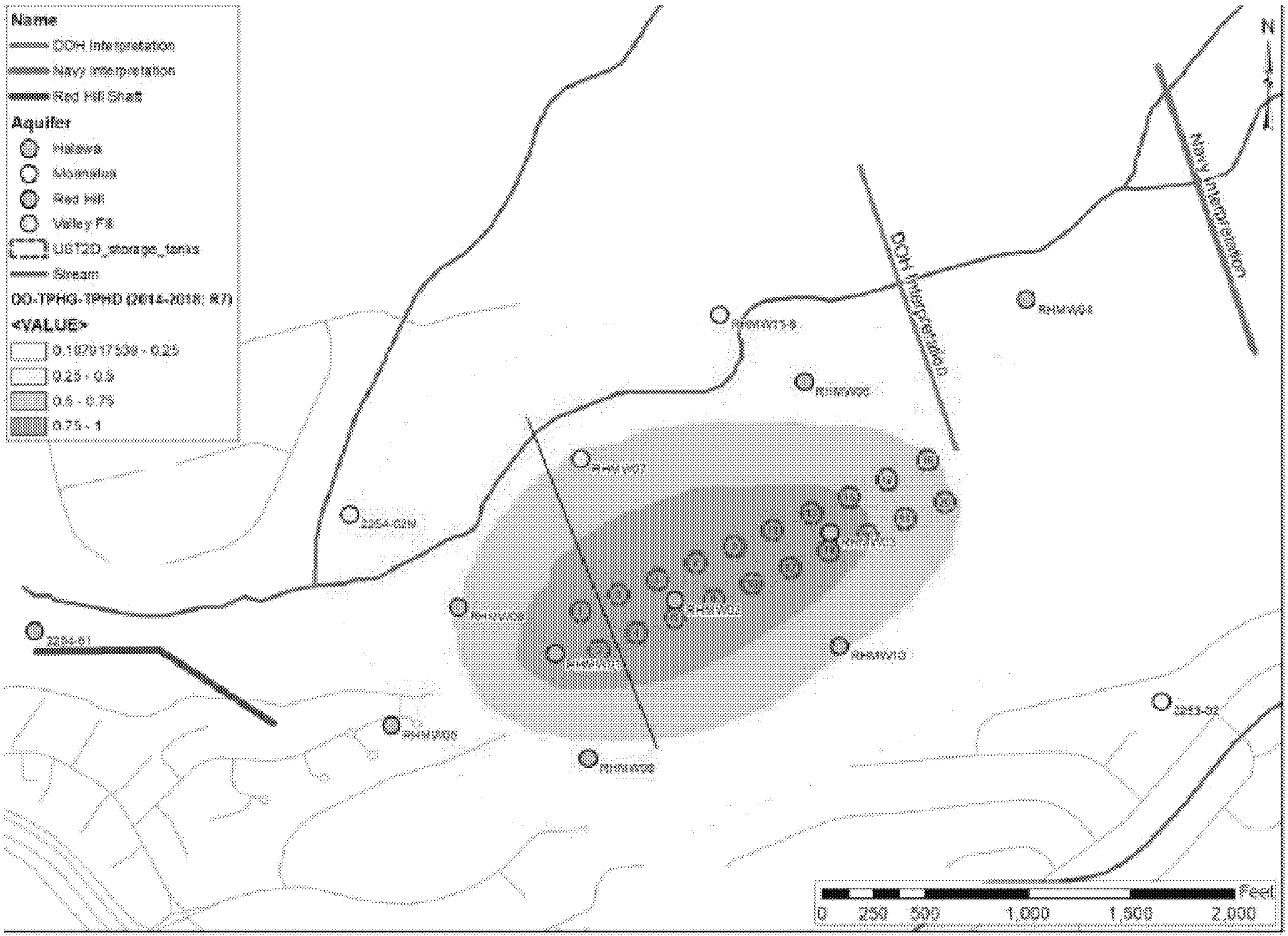
A good idea, but challenging in application

Consistency Criteria are Non-Unique



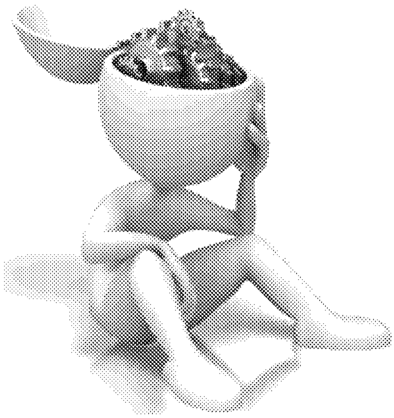
- First issue is complexity of system
  - vs. lumped homogeneous model
- Second is geometry vs. observations
  - I.E., flow may not follow dip
- Vapor data are most dense data set
  - In both time & location
- Controls over vapor migration include:
  - Source distribution & mass vs. time
    - And directional implications
  - Diffusive and advective vapor transport
- G.W. data are too sparse to constrain
  - Particularly if actual migration was to NW

Source vs. Observations



DRAFT for Regulator Review and Discussion Purposes Only

Lots to Think About – In Summary



- Various regulatory issues are linked
- We like that the modeling is dynamic
  - And computationally efficient
  - Creative use of Richards assumptions
- To move forward, if that is the choice, we need;
  - Define & defend EPM assumption & scale
  - Heterogeneous model using site geology
  - Parameters defined for each HSU
  - Determine range of background conditions
- Include fast-track features
  - Define continuity of these

A Few Useful References

- André J. A. Unger; Boris Faybishenko; Gudmundur S. Bodvarsson; Ardyth M. Simmons, 2004. ***Simulating Infiltration Tests in Fractured Basalt at the Box Canyon Site, Idaho.*** Vadose Zone Journal (2004) 3 (1): 75-89.
- J. C. S. Long, J. S. Remer, C. R. Wilson, P. A. Witherspoon, 1982. ***Porous Media Equivalents for Networks of Discontinuous Fractures.*** Water Resources Research, Vol. 18, No.3, Pages 645-658, June 1982.
- Interstate Technology and Regulatory Council, 2017. ***Characterization and Remediation of Fractured Rock***.
- National Research Council 1996. ***Rock Fractures and Fluid Flow: Contemporary Understanding and Applications***. Washington, DC: The National Academies Press. https://doi.org/10.17226/2309.
- National Academies of Sciences, Engineering, and Medicine. 2015. ***Characterization, Modeling, Monitoring, and Remediation of Fractured Rock.*** Washington, DC: The National Academies Press.
- National Research Council 2001. ***Conceptual Models of Flow and Transport in the Fractured Vadose Zone.*** Washington, DC: The National Academies Press. https://doi.org/10.17226/10102
- Daniela Blessent, Peter R. Jørgensen, and Ren´e Therrien, 2014. ***Comparing Discrete Fracture and Continuum Models to Predict Contaminant Transport in Fractured Porous Media.*** Vol. 52, No. 1–Groundwater, 2014.
- Pankow, J.F., R.L. Johnson, J.P. Hewetson, and J.A. Cherry, 1986. ***An Evaluation of Contaminant Migration Patterns at Two Waste Disposal Sites on Fractured Porous Media in Terms of the Equivalent Porous Medium (EPM) Model***. J. of Cont. Hydrology, 1:65-76.